Cluster Distances: the Good, the Bad and the Ugly

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Abstract. Galaxy clusters are important targets for peculiar velocity studies as a direct comparison of the various distance indicators can be made. The potential problem of an environmental effect biasing the distances to clusters of different richness is examined. The level of intrinsic cluster-to-cluster variations is also reviewed. We investigate the claim that the derived Fundamental Plane (FP) distances vary systematically with FP scatter. The cluster distances and peculiar velocities derived from Tully-Fisher, FP and Brightest Cluster Galaxies are compared and we find good agreement.

1. Introduction

A number of early attempts to measure cluster distances could be described as *ugly* by current standards. In particular, many early studies suffered from poorly determined systematic errors. A few early studies were wrong due to erroneous data, i.e. *bad*. As the field has developed a considerably better understanding of the practical problems associated with cluster distance measurement have emerged and hopefully reliable (*good*) distances are now starting to appear. The new surveys are starting to provide a sizable set of clusters that possess both good Tully-Fisher (TF) and Fundamental Plane (FP) data.

Here we address three aspects of cluster distances:

- At what level do environmentally dependent stellar population biases affect the FP cluster distance determinations?

- Do the derived FP distances vary systematically with FP scatter?

- How well do the different cluster distance indicators compare?

We use the SMAC FP dataset to investigate these themes. For this dataset the random and systematic errors in the velocity dispersion (σ) measurements are 0.025 dex and 0.015 dex respectively. For the Mg_2 indices these errors are
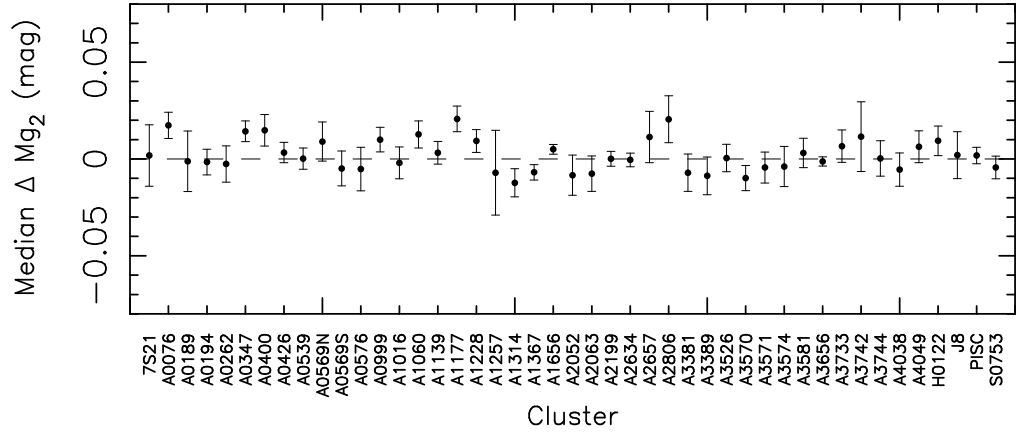
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Figure 1. Variation of the cluster $Mg_2 - \sigma$ relation zero-points. The median ΔMg_2 values and their uncertainties are displayed for the 45 SMAC clusters that have Mg_2 measurements. Three clusters (i.e. A76, A347 and A1177) are offset by more than two standard deviations.

0.010 mag and 0.002 mag respectively. Hence this dataset is the highest precision and largest FP dataset that is currently available.

2. Stellar population biases in the FP cluster distances

The systematic variation in the stellar populations of elliptical and S0 galaxies with the environment has long been suggested, e.g. Larson, Tinsley & Caldwell (1980). While such an effect on the FP distance indicator is probably only at the level of ∼0.02 dex between the dense cluster cores and isolated field regions (Lucey 1995), this may produce a bias in the derived distances for poor and rich clusters.

We have examined the cluster-to-cluster offsets in the $Mg_2 - \sigma$ relation. Following Colless et al. (1999), in Figure 1 we show the median ΔMg_2 and uncertainty for each cluster. The SMAC clusters display a remarkable degree of homogeneity with a measured scatter in ΔMg_2 of only 0.006 mag. If the cluster $Mg_2 - \sigma$ relation is universal then there is a probability of 0.045 that the measured χ^2 would be observed. In order to derive a reduced χ^2 of unity an intrinsic rms scatter of 0.004 mag must be added. As the expected ΔMg_2 variation due to the known level of systematic errors is ∼0.003 mag, there is no evidence for any significant cluster-to-cluster variation in the $Mg_2 - \sigma$ relations. The true intrinsic ΔMg_2 scatter is less than 0.004 mag. This limit is 4× smaller than that found for the EFAR sample (Colless et al. 1999).

Stellar population models imply that if Mg_2 differences are caused by age differences then a 0.004 mag change in ΔMg_2 translates into a luminosity change that would give an apparent distance shift of 0.02 dex (see e.g. Jorgensen et al. 1996). This is equivalent to a 340 km s^{-1} shift at the Coma cluster distance. If stellar population differences were responsible for some component of the FP peculiar velocities we would predict these to be correlated with ΔMg_2. Following
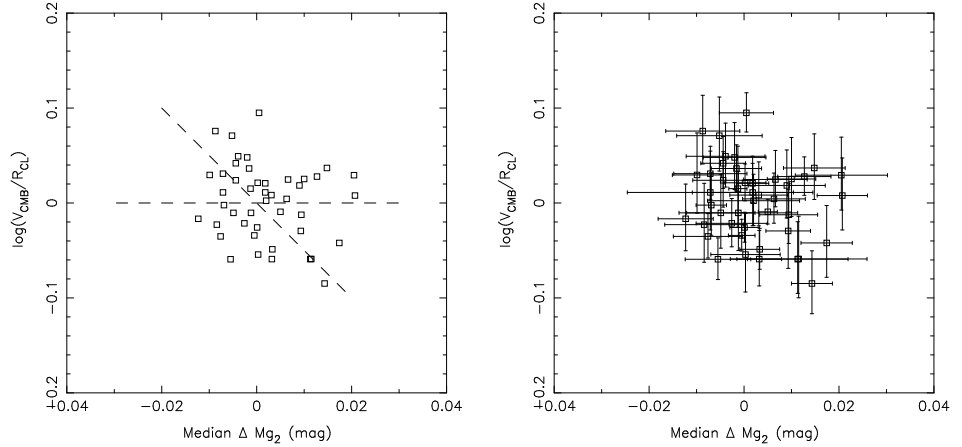
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Figure 2. Is cluster peculiar velocity correlated with ΔMg_2? The median ΔMg_2 for each SMAC cluster is plotted against $\log_{10}(V_{CMB}/R_{CL})$. The left hand panel shows the data with no error bars displayed. The inclined dashed line shows the expected correlation if the galaxy luminosities are affected by small age differences. If all the cluster galaxies in the sample were homogeneous then the data is expected to display no correlation, i.e. the horizontal dashed line. The right hand panel shows the data with the error bars plotted.

Burstein, Faber & Dressler (1990), we use the quantity $\log_{10}(V_{CMB}/R_{CL})$ as a measure of the cluster peculiar velocity. V_{CMB} is the cluster velocity in the local CMB rest frame and R_{CL} is the derived cluster distance. In Figure 2, we present the correlation between ΔMg_2 and $\log_{10}(V_{CMB}/R_{CL})$. If the galaxy luminosities are affected by age differences then a slope of –5 is expected. Unfortunately the relatively large errors do not allow a meaningful constraint to be placed on this correlation; the best fit slope allowing for the errors in both co-ordinates is -18 ± 90. For clusters with $\Delta Mg_2 < 0.0$ the mean $\log_{10}(V_{CMB}/R_{CL})$ value is 0.011 ± 0.008 whereas for clusters with $\Delta Mg_2 > 0.0$ the value is 0.004 ± 0.008. We conclude that there is no evidence that age differences bias the FP distances for the SMAC sample.

If such a stellar population bias existed, in order to cause a spurious bulk flow signal the ΔMg_2 residuals would need to be correlated on the sky. For the SMAC sample this is not the case and the bulk flow measurement is only weakly affected. If a ΔMg_2 term is included in the distance indicator the SMAC bulk flow measurement *increases* by ~ 70 km s^{-1}.

3. Is the cluster peculiar velocity related to FP scatter?

Using mostly literature FP data for 20 rich clusters, Gibbons, Fruchter and Bothun (1998) have recently suggested that clusters which have a lower FP rms scatter also possess a lower peculiar velocity and vice versa. In the left hand panel of Figure 3 we reproduce their plot of FP scatter versus peculiar velocity. They propose two sub-groups with the division at an FP rms scatter of ~ 0.07 in
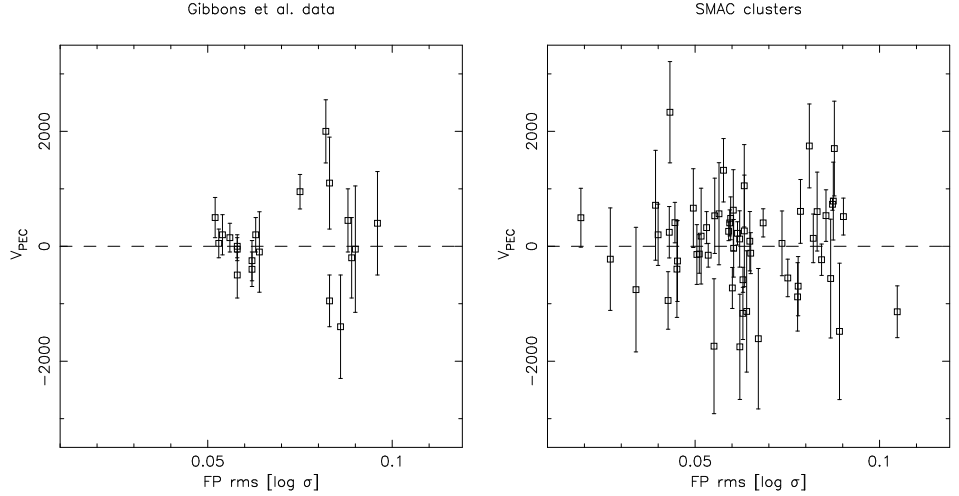
Figure 3. The relationship between FP scatter and peculiar velocity. The left hand panel displays the Gibbons et al. data and the right hand panel displays the SMAC cluster data.

units of $\log_{10} \sigma$. For this sample, the lower FP scatter clusters have an average absolute peculiar velocity of 220 ± 50 km s^{-1} (n=11) whereas the higher FP scatter clusters have a value of 830 ± 200 km s^{-1} (n=9). They suggest that the measured peculiar velocities for the higher FP scatter group of clusters are not real but due to a systematic difference in the FP relation.

The equivalent plot for the SMAC clusters is shown in the right hand panel of Figure 3. For the 39 clusters which have an rms FP scatter less than 0.07, the average absolute peculiar velocity is 610 ± 90 km s^{-1}. For the 17 clusters with an FP rms scatter greater than 0.07, the average value is 760 ± 120 km s^{-1}. If we consider only the well sampled clusters ($n_{GAL} \geq 10$), which are less affected by outliers, the lower and higher FP scatter groups have an average absolute peculiar velocity of 560 ± 110 km s^{-1} (n=16) and 690 ± 150 km s^{-1} (n=9) respectively. Thus for the SMAC sample there is no evidence for a trend of peculiar velocity with FP scatter.

4.   Comparison of the BCG, TF and FP results

Direct comparison of the cluster distances derived from different indicators is a valuable test of systematics. In this section we compare results from the FP work of SMAC with the Brightest Cluster Galaxy (BCG) study of Lauer & Postman (1984) (LP) and the TF study of Giovanelli et al. (1999) (SCI/II). The average errors in the cluster distance measurements for the SMAC, LP and SCI/II samples are 0.026, 0.081 and 0.022 dex respectively.

One potential problem is that different surveys don't always select precisely the same physical structure. In particular, FP samples concentrate on the cluster core whereas TF samples cover a wider spatial area. If different physical structures are selected then this may result in a disagreement in the mean red-
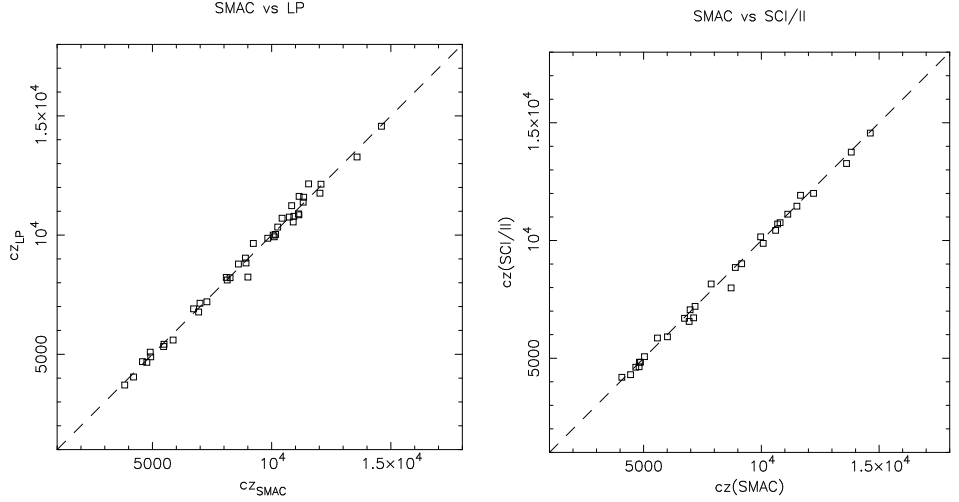
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Figure 4. Comparison of the SMAC cluster velocities with those of LP and SCI/II. The most discrepant cluster is A4038 for which both LP and SCI/II have a velocity of 740 $km\,s^{-1}$ less than that used by SMAC. This difference is due to confusion with the adjacent A4049 cluster.

shift adopted for the cluster. In Figure 4 we compare the cluster redshifts used by SMAC with those of LP and SCI/II. The agreement is good with an average absolute velocity difference of 180 $km\,s^{-1}$.

In Figure 5 we present the distance-distance comparisons of SMAC with LP and SCI/II. The SMAC and LP distances are in reasonable agreement; there is a probability of 0.06 that the measured χ^2 would arise given the distance errors. The SMAC and SCI/II distances are in better agreement with a χ^2 probability of 0.13.

The SMAC-LP and SMAC-SCI/II peculiar velocity comparisons are presented in Figure 6. For both comparisons the agreement is again reasonable for the measurement errors. For the SMAC-LP comparsion there is a probability of 0.15 that the observed χ^2 would arise given the peculiar velocity errors. For the SMAC-SCI/II comparison the probability is 0.08. In this comparison most clusters are in good agreement and form a tight group of points at the centre of the plot. This is further illustrated in Figure 7 where we display the differences in the measured peculiar velocities. The most discrepant cluster is Hydra(A1060); $V_{PEC}(\text{SMAC}) = +260 \pm 183$ $km\,s^{-1}$, $V_{PEC}(\text{SCI/II}) = -320 \pm 142$ $km\,s^{-1}$.

5. Conclusions

We have used the SMAC data to address three aspects of cluster distances and have concluded that:

1. While there is no evidence for significant differences in the stellar populations of the SMAC FP cluster sample as determined by the $Mg_2 - \sigma$
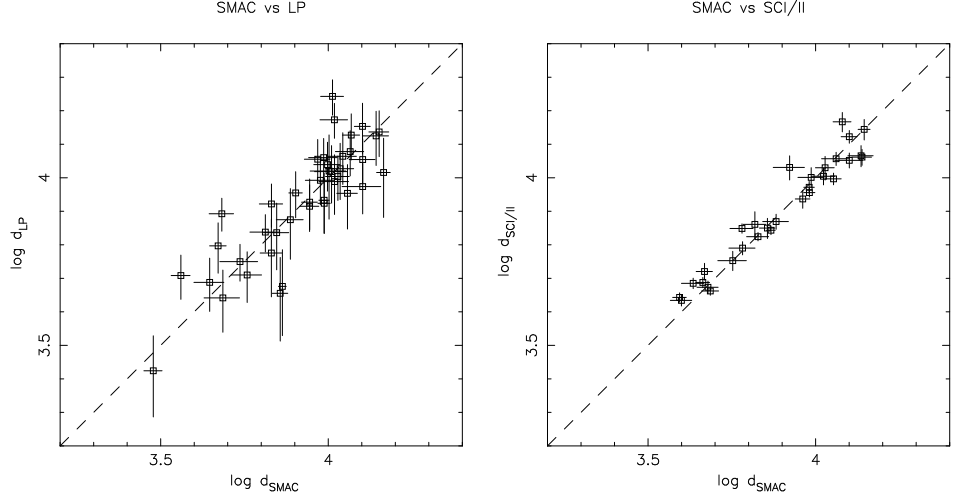
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SMAC vs LP   SMAC vs SCI/II

Figure 5.   Comparison of the SMAC cluster distances with those of
LP and SCI/II. For the SMAC-LP comparison there are 41 clusters in
common. Four clusters are formally discrepant; A262 (3.4σ), Hydra
(=A1060) (2.1σ), A3381 (3.7σ), and A3733 (2.3σ). For the SMAC-
SCI/II comparison there are 30 clusters in common; Centaurus (A3526)
is excluded from the comparison because of the different treatment of
the Cen30 and Cen45 subcomponents. Two clusters are discrepant;
A957 (2.2σ) and Hydra (2.0σ).
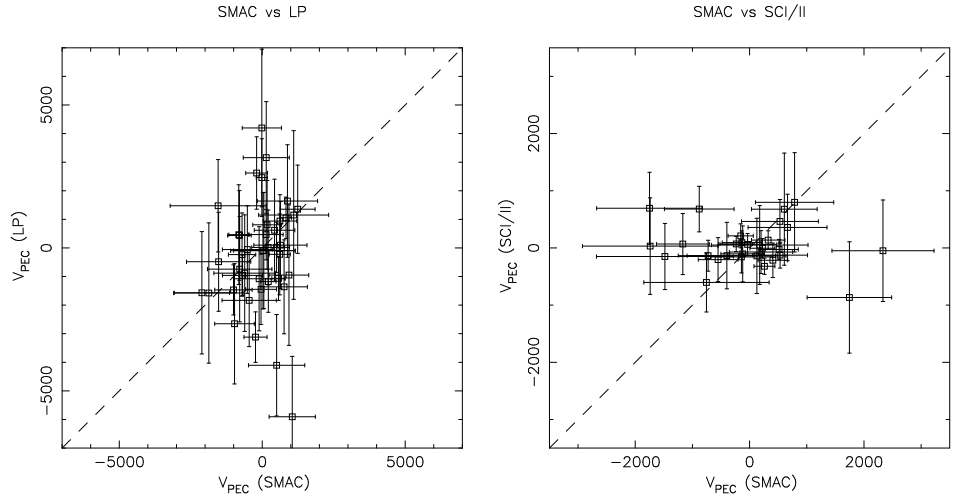

SMAC vs LP   SMAC vs SCI/II

Figure 6.   Comparison of the SMAC peculiar velocities with those of
LP and SCI/II. The scale for the right hand panel is half that of the
left hand panel. For the SMAC-LP comparison, the larger error for LP
distance measurements spreads the clusters vertically. For the SMAC-
SCI/II comparison a few discrepant clusters are spread horizontally
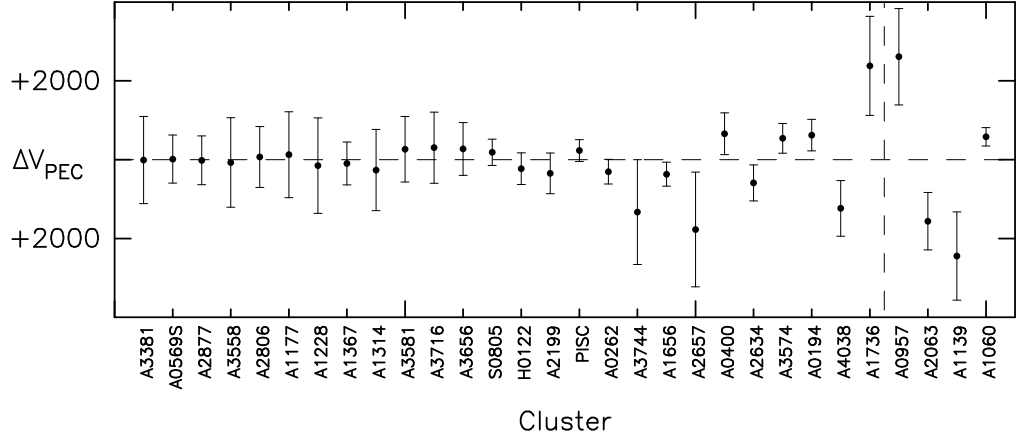because SMAC measures, on average, larger individual cluster peculiar
velocities.

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Figure 7. The differences in the cluster peculiar velocities as measured by SMAC and SCI/II. The clusters are plotted in order of the significance of the difference. Clusters that lie to the right of the vertical dashed line are discrepant at greater than the 2σ level.

relation, this is a relatively poor tool to assess if intrinsic cluster-to-cluster variations bias the FP distances.

2. The SMAC dataset of 56 clusters does not support the claim made by Gibbons, Fruchter and Bothun (1998) that the FP scatter is related to cluster peculiar velocity.

3. The SMAC FP and LP BCG distances are in reasonable agreement with only four out of 41 clusters being discrepant at greater than the 2σ level. The SMAC FP and SCI/II TF distances are in good agreement with only two out of 30 clusters discrepant at greater than the 2σ level.

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